REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
23.Jan.04

3. REPORT TYPE AND DATES COVERED
THESIS

4. TITLE AND SUBTITLE
"AN ERGONOMIC AND HUMAN FACTORS COMPARISON BETWEEN MANUAL AND TELEROBOTIC SIMULATED ENDOSCOPIC SURGERY"

5. FUNDING NUMBERS

6. AUTHOR(S)
MAJ LEE ERNEST C

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
HARVARD UNIVERSITY

8. PERFORMING ORGANIZATION REPORT NUMBER
CI04-25

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20040219 105

14. SUBJECT TERMS

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

Title Page

An ergonomic and human factors comparison between manual and telerobotic simulated endoscopic surgery

January 8, 2004

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Abstract

Background: The objective of this study was to perform an ergonomic and human factors comparison between manual and telerobotic simulated endoscopic surgery.

Methods: To evaluate and compare the ergonomics of endoscopic surgery using manual and telerobotic techniques, 13 participants without experience as primary surgeons in endoscopic surgery were selected to perform a set of simulated tasks at random. The tasks consisted of passing a pompom through rings, suturing, running a 32-in ribbon, and cannulation. The Job Strain Index (JSI) and Rapid Upper Limb Assessment (RULA) were used for ergonomic evaluation. Participants completed a questionnaire comparing intuitiveness and mental stress.

Results: JSI and RULA scores for all four tasks demonstrated that the telerobotic technique is ergonomically more favorable than the manual technique. The telerobotic technique is as intuitive and no more stressful than the manual technique.

Conclusions: Telerobotic endoscopic surgery is ergonomically more favorable, equally intuitive, and no more mentally stressful than manual endoscopic surgery.

Key words: Endoscopic – Robot – Ergonomic – Zeus – Surgery

Introduction

Advances in the development of computer assisted surgical systems now allow the surgeon to control robotic instruments and arms with the number of degrees of freedom required for complex surgeries in a comfortable and very natural manner. Computers provide the interface between the robotic arms and the surgeon's hands. They extend the surgeon's capabilities beyond conventional surgical techniques, thus adding new capabilities that previously had not been possible with conventional surgery [4].

Telerobotic surgical systems such as Zeus (Intuitive Surgical, Sunnyvale, California) are intended to control endoscopic instruments during surgical procedures. The Zeus Surgical Robotic System replaces the surgeon's hands with robotic instruments as well as holds the camera. The telerobotic system serves in a master slave relationship for the surgeon. The system uses 3-D imaging to immerse the surgeon in a three-dimensional video operating field [1]. The natural operative field and hand eye orientation found in open surgery is maintained. The Zeus system places instrument movements under direct real-time control. A surgeon's open techniques at the console are instantly converted into minimally invasive surgery at the surgical site.

Telerobotic endoscopic surgery offers potential solutions to the pitfalls of its manual counterpart. Compared to open surgery, manual endoscopic surgery involves more awkward and static movements of the upper extremities, limits natural changes in body posture and may induce fatigue, and requires relatively high muscular loading, putting surgeons at risk for fatigue and injury [10]. Manual endoscopic surgery instruments have less efficient handle-to-tip force transmission than open surgery

instruments, and cause excessive flexion and ulnar deviation of the surgeon's wrist due to fixed-point insertion and the large external arc of arm movements required due to increased instrument length [10]. Manual endoscopic surgeons also report significant finger numbness and eyestrain compared to surgeons who operate using mainly open techniques. Berguer et al found that manual endoscopic surgery is more mentally stressful and requires more concentration than open surgery [2]. Surgical instrument designers are constantly searching for methods by which to ease the stress introduced by manual endoscopic surgery.

Telerobotic endoscopic surgery offers three-dimensional video displays, provides surgeons with mechanical advantages, and significantly reduces the external arc of arm movements. Nio found that telerobotic endoscopic surgery can be performed equally or more precisely than manual endoscopic surgery [9]. Telerobotic endoscopic surgery systems make audio-visual telementoring possible. Until now, the broad use of telerobotic endoscopic surgery systems has been limited due to high investment and running costs; however, new technological concepts may result in significant cost reduction.

Material and Methods

Human research approval for the experiment was obtained from the Virginia Commonwealth University Institutional Review Board and the Harvard School of Public

Health Human Participants Committee. The experiment was carried out at the Virginia Commonwealth University Health Science Center campus.

Thirteen volunteer participants, without experience as primary surgeons in either manual or telerobotic endoscopic surgery, were selected to perform four common simulated surgical tasks (passing a pompom through rings, suturing, running a 32-in ribbon, and cannulation), using each of two techniques (manual and telerobotic). Four participants were medical students. The remaining nine were junior medical or surgical residents. Five participants had experience as primary surgeons using open technique. One participant had extensive video game experience. The other twelve participants had minimal video game experience. Scales for translation of movements in linear direction and rotation were set at medium settings.

A KC-135 surgical simulator box was used for all tasks (Figure 1). A standard laparoscopic camera was placed in the simulator box. For the telerobotic setup, the two robotic arms of the Zeus Surgical Robotic System were placed in the simulator box. The two arms, fitted with needle grasper instruments with micro-wrist action, were controlled by the participant seated at a remote control console in a chair with armrests. For the manual endoscopic technique, two standard laparoscopic needle holders were placed in the simulator box. The manual instruments were similar to the robotic instruments but lacked micro-wrist flexion and extension capability. 2-dimensional video monitors were used for both manual and telerobotic simulated endoscopic surgery.

Participants were given a description of each task and of both operative techniques. They were instructed how to operate both the manual laparoscopic instruments and the telerobotic system. Participants performed each task utilizing both

manual telerobotic endoscopic surgery techniques. Randomization ensured that some participants completed the four tasks utilizing the telerobotic technique first, while the remaining participants completed the four tasks using the manual technique first. Participants were allotted a maximum of fifteen minutes to complete each task.

Tasks

Pompom-through-rings

This task consisted of passing a 1.5-cm red pompom through seven 2-cm diameter metal rings (Figure 2). The rings were oriented vertically and parallel to one another, and spaced approximately 1-cm from one other. This task simulates passing items from grasper to grasper within a common plane.

Suturing

The participant was instructed to place three running sutures into a Simulab silicone wound model using 2.0 silk material on a curved tapered needle (Figure 3). To keep techniques standardized, the initial knot was pre-tied. No final knot was made after completion of the three suture passes.

Ribbon-passing

This task consisted of running a 32 x ¼-in cloth ribbon from end-to-end using two needle holders. The ribbon had a zigzag pattern (Figure 4). This task simulates running tissue such as bowel for visual inspection to check for lesions.

Cannulation

A yellow pipe cleaner 1-in in length was passed through the lumen of an orange neoprene tube of½-in length (Figure 5). The lumen was approximately 3-mm in diameter. Participants were allowed to sandwich the tube between the floor plate of the simulator box and one of the needle driver tips if they wished. Most elected to hold the tube within the a single needle driver's tips while passing the pipe cleaner through with the other needle driver.

Analysis

A Sony mini-DV camera was positioned so that the left frontal-lateral aspect of each participant was in view as they performed the tasks. All tasks were recorded on mini-DV tapes for later review by an observer. Biomechanical models were then applied to the video images to predict internal tissue exposures.

Rapid upper limb assessment (RULA) was used to assess the postures of the neck, trunk, and upper limbs along with muscle function and the external loads experienced by the participant's body. A coding system was used to generate an action list that indicates the intervention level required to reduce the risks of injury due to physical loading. RULA provides a simplified and conservative rating system that can be used to indicate whether or not the static loading or forces exerted during a given task will cause fatigue and subsequent tissue damage. McAtmney and Corlett have previously reported on the initial validation and reliability studies of RULA [6].

Likewise, the job strain index (JSI) was also used to predict internal exposure. JSI involves the measurement or estimation of six task variables (intensity of exertion,

duration of exertion, efforts per minute, wrist posture, speed of exertion, and duration of task per day). Moore and Garg [7] have described JSI methodology and preliminary validation in a prior study. Participants were instructed to complete each task at a comfortable pace; thus, the rating for speed of work was set to "slow". The multiplier for the duration of task per day was set at four hours.

Each participant was given a maximum of fifteen minutes to complete each task. For tasks not completed within this allotted time period, both the JSI and RULA scoring systems were applied over the maximum 15-min period.

Immediately after completing all tasks, each participant completed a questionnaire that compared the intuitiveness and perceived mental stress between all four telerobotic endoscopic surgery tasks to all four manual endoscopic surgery tasks. Intuitiveness and perceived mental stress were graded on a scale from 1 to 10, with 1 being the least favorable response and 10 being the most favorable.

The Wilcoxon-Signed-Rank Exact Test was used to compare differences between the two techniques. Data are presented in mean JSI and RULA scores and mean overall ratings for intuitiveness and mental stress between telerobotic and manual endoscopic surgery techniques. 95% confidence limits and *p*-values are also presented. Significance was defined as a 2-sided *p*-value of less than 0.05. Statistical analysis was performed using StatXact-5 for Windows.

Results

All participants succeeded in completing the pompom-through-rings, ribbon-passing, and cannulation tasks using both techniques (manual and telerobotic). Four participants did not complete the suturing task within the allotted fifteen minutes using the telerobotic technique. One participant did not complete the suturing task within the allotted time using the manual technique. Another participant abandoned the suturing task using the manual technique after complaining of significant discomfort in her hands. Seven participants completed the four tasks utilizing the telerobotic technique first, and then using the manual technique. The remaining six utilized the manual technique first and then repeated the same tasks using the telerobotic technique.

JSI scores for all four tasks demonstrated with statistical significance that the telerobotic technique is ergonomically more favorable than the manual technique (Table 1). Moore and Garg [7] found an increase in mean incidence rate for upper extremity disorders with an increase in JSI score.

The median JSI score for the pompom-through-rings task using the manual technique was 13.5 (range 9.0-27.0) vs 3.0 (range 2.3-4.5) for the telerobotic technique. The median JSI score for suturing using the manual technique was 20.3 (range 13.5-27.0) vs 4.5 (range 3.0-9.0) for the telerobotic technique. The median JSI score for ribbon-passing using the manual technique was 6.8 (range 3.4-9.0) vs 1.5 (range 1.1-2.3) for the telerobotic technique. The median JSI score for cannulation using the manual technique was 4.5 (range 3.0-6.8) vs 1.1 (range 0.4-1.5) using the telerobotic technique.

RULA scores for all four tasks demonstrated with statistical significance that the telerobotic technique is ergonomically more favorable than the manual technique. (Table 2). RULA scores can range from 1 to 7 based upon the estimated risk of injury due to

musculoskeletal loading. A score of 1 or 2 indicates a given job posture is acceptable if not maintained or repeated for long periods. A score of 3 or 4 indicates further investigation is needed and changes may be required. A score of 5 or 6 indicates that changes are required soon. A score of 7 indicates that changes are required immediately [6].

The median RULA score for the pompom-through-rings task using the manual technique was 6.0 (range 6.0-7.0) vs 3.0 (range 3.0-3.0) for the telerobotic technique. The median RULA score for suturing using the manual technique was 7.0 (range 6.0-7.0) vs 3.0 (range 3.0-3.0) for the telerobotic technique. The median RULA score for ribbon-passing using the manual technique was 6.0 (range 6.0-7.0) vs 3.0 (range 3.0-3.0) for the telerobotic technique. The median RULA score for cannulation using the manual technique was 6.0 (range 6.0-6.0) vs 3.0 (range 3.0-3.0) for the telerobotic technique.

No statistically significant difference was found for both mental stress and intuitiveness scores between the manual and telerobotic simulated endoscopic surgery (Table 3). The median intuitiveness score for the manual technique was 7 (range 5-10) vs 8 (range 5-9) for the telerobotic technique. The median mental stress for the manual technique was 6 (range 1-8) vs 5 (range 1-7) for the telerobotic technique.

Mean JSI scores comparing manual and telerobotic simulated endoscopic surgery for all four tasks are shown in Figure 6. Likewise, mean RULA scores are shown in Figure 7. Mean subjective scores for mental stress and intuitiveness between manual and telerobotic simulated endoscopic surgery are shown in Figure 8.

Discussion

Previous studies have shown that manual endoscopic surgery exposes surgeons to awkward movements of the upper extremities, limits natural changes in body posture, and requires relatively high muscular loading. Such exposure puts surgeons at risk for fatigue and injury [8]. Telerobotic surgery offers potential solutions to these problems by providing surgeons with mechanical advantages and significantly reducing the external arc of arm movements required.

In this repeated measures study, two different biomechanical models (JSI and RULA) were applied to video images of participants performing four simulated surgical tasks to predict internal tissue exposures. Both RULA and JSI scores for all four tasks demonstrate with statistical significance that telerobotic simulated endoscopic surgery exposes the surgeon to less risk of musculoskeletal injury than manual simulated endoscopic surgery.

A repeated measures study design eliminates inter-subject variability. By analyzing controlled simulated tasks rather than actual surgeries, unpredictable variables such as variations in procedure, unexpected anatomy, and varying operating room setups were controlled for.

Simulated surgery may not be predictive of actual surgery with many unpredictable variables. Nevertheless, this controlled repeated measures experiment using an endoscopic surgical simulator box provided an objective means of evaluating the ergonomics of both manual and telerobotic endoscopic surgery systems. Body posture measurements were required to obtain JSI and RULA scores. Random errors may have been introduced as these measurements were estimated from video analysis.

Although large-scale controlled studies are still needed to further validate and update existing JSI and RULA methodologies, both evaluation systems have already undergone preliminary validation.

Participants also rated intuitiveness and perceived mental stress between manual and telerobotic surgery techniques on a scale from 1 to 10. Despite the fact that participants had to familiarize themselves to the telerobotic endoscopic surgery system, we found no difference in intuitiveness and mental stress experienced between manual and telerobotic techniques.

In our study, the endoscopic camera was positioned over the operative site and oriented so that the direction of instrument movement on the screen matched the actual movement of the participant's hands. For example, if a participant moved an instrument to the right, the image of the instrument on the monitor also moved to the right. In actual surgery, oftentimes this is not the case. With telerobotic endoscopic surgery systems, the natural operative field and hand eye orientation found in open surgery is maintained. So in an actual surgery, a surgeon might find telerobotic endoscopic surgery more intuitive and less mentally stressful than manual endoscopic surgery.

Several participants commented that operating in a seated position rather than a standing one was appealing. The Zeus Surgical Robotic System allows a surgeon to adjust how much rotational and linear movement at the controller is amplified at the effecter robotic arms. This feature provides an ergonomic benefit; however, extreme movement amplification should be avoided in order to minimize magnification of unintentional small movements.

Intuitive Surgical has given notice that the Zeus system is being phased out in favor of the da Vinci surgical system. The latter system provides a three-dimensional view of the operative site. With the da Vinci system, the surgeon inserts two fingers into a glove-like controller. This system provides a superior way to immerse the surgeon into a computer-created environment that makes one think and feel as if he or she is actually operating at a remote operative site. These features of the da Vinci system will likely make the telerobotic operative experience more intuitive and easier to learn for new surgeons.

Future studies might address human factors and ergonomics comparisons between open surgery and telerobotic endoscopic surgery using the da Vinci surgical system. Many participants believed adding tactile and force feedback (haptic technology) would drastically enhance surgeon performance and make the system more intuitive. Ironically, many telerobotic surgeons feel that adding haptic technology is not necessary; however, these surgeons are probably choosing operative cases very carefully, knowing that their only cues during the operation will be visual. Adding haptic technology to telerobotic surgical systems could open up vast new frontiers in telerobotic surgery. We should also note that several participants bent suture needles and crushed the plastic base plate at the operative site while using the telerobotic technique. Although this is not likely to be a problem with experienced telerobotic surgeons, addition of haptic feedback would likely prevent such problems in novice surgeons.

Another issue that must be addressed is the time delay that occurs when a surgeon uses a telerobotic system to operate on a patient located thousands of miles away. For example, a surgeon in the United States may wish to operate on a patient located in a

remote village on the other side of the earth, or on an astronaut inside the orbiting International Space Station. In such cases, there will be a slight delay between the time the surgeon inputs movement commands and the time the telerobotic arms actually execute the procedure at the operative site.

Despite the challenges yet to be resolved, the use of telerobotic endoscopic surgery systems opens up a vast array of possibilities never before imagined with conventional surgical techniques. These include: increased three-dimensional accuracy, increased precision of movements, reproducibility of repeated procedures, and the ability to perform surgery from a distance [3, 5]. Technological advancements and an increased demand for telerobotic surgery systems may soon result in decreased cost.

Eventually, advancements in telerobotic systems will likely provide surgeons with practical robust solutions to overcome the current limitations of manual open and endoscopic surgery. For example, researchers are searching for a way to synchronize the telerobotic arms and endoscopic camera to a beating heart. This would simplify and shorten the time of some cardiac operative procedures, which in turn would decrease personnel and material resources required. Conceivably, telerobotic surgeons could operate on three-dimensional MRI images while telerobotic arms would operate on the actual tissue. No longer would surgeons need to correlate MRI images with the actual organ or tissue site of interest.

Telerobotic surgery offers one other type of benefit to surgeons. Because they remove the surgeon from the direct operative field, the chance of acquiring a blood borne pathogen infection such as HIV or hepatitis C is greatly reduced. This would be particularly true in the case of orthopedic surgery requiring much mechanical

manipulation such as grinding, drilling, chiseling, and hammering. The technology utilized in telerobotic surgical systems can also be applied to non-medical fields. Telerobots can be used to perform hazardous duties such as diffusing bombs or sandblasting lead based paint, essentially removing humans from hazardous exposure sites and obviating or at least minimizing the need for personal protective equipment.

In conclusion, telerobotic endoscopic surgery is ergonomically more favorable, equally intuitive, and no more mentally stressful than manual endoscopic surgery when performing four basic operative tasks in a simulated environment.

The following is a mandatory US Air Force clause that must be placed at the end of the article, since the corresponding author is an active duty Air Force officer.

The views expressed in this letter are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the US Government.

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Table 1. Mean difference for JSI Scores between simulated manual and telerobotic endoscopic surgical techniques.

Task	Mean difference	95% Confidence limit	*p*-value
Pom-pom rings	11.3	[7.7,14.8]	<0.0002
Suturing	12.0	[9.2,14.7]	<0.0002
Ribbon-passing	4.9	[4.0,5.9]	<0.0002
Cannulation	3.9	[3.1,4.6]	<0.0002

Table 2. Mean difference for RULA Scores between simulated manual and telerobotic endoscopic surgical techniques.

Task	Mean difference	95% Confidence limit	*p*-value
Pom-pom rings	3.4	[3.1,3.7]	<0.0002
Suturing	3.7	[3.4,3.9]	<0.0002
Ribbon-passing	3.2	[2.9,3.4]	<0.0002
Cannulation	3.0	[3.0,3.0]	<0.0002

Table 3. Mean difference for intuitiveness and mental stress scores between simulated manual and telerobotic endoscopic surgical techniques.

	Mean difference	95% Confidence limit	*p*-value
Intuitiveness	0.3	[-0.9,1.4]	<0.65
Mental stress	0.5	[-0.7,1.6]	<0.39

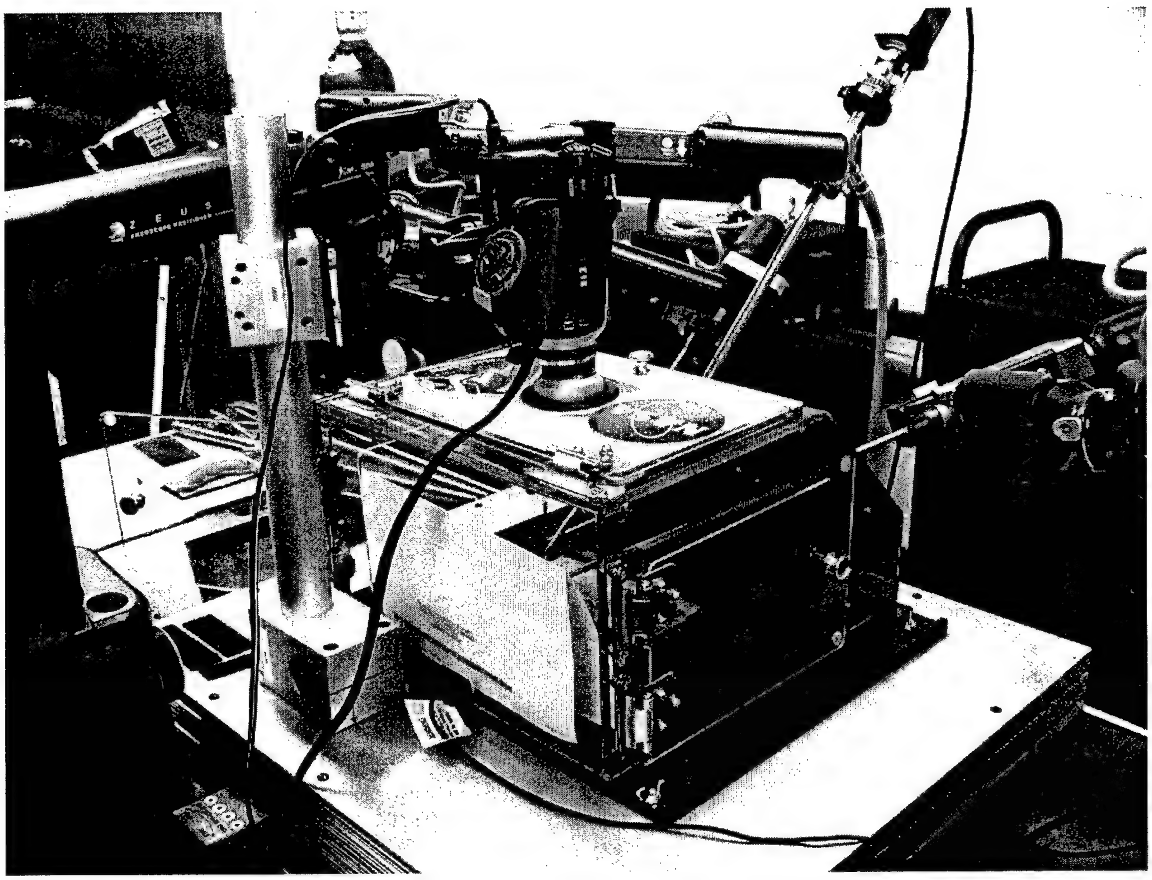

Figure 1. Telerobotic (Zeus) arms with KC-135 surgical simulator.

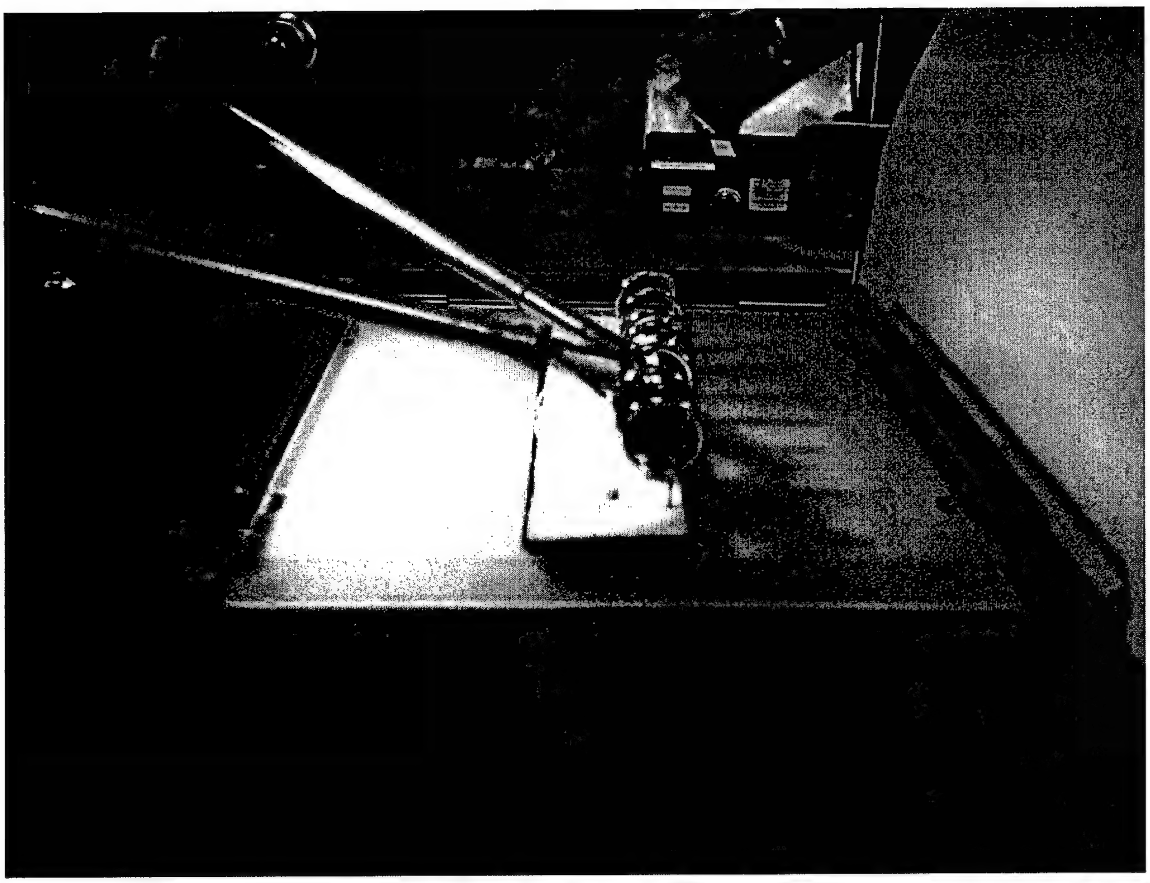

Figure 2. Passing a 1.5-cm pompom through seven 2-cm diameter metal rings.

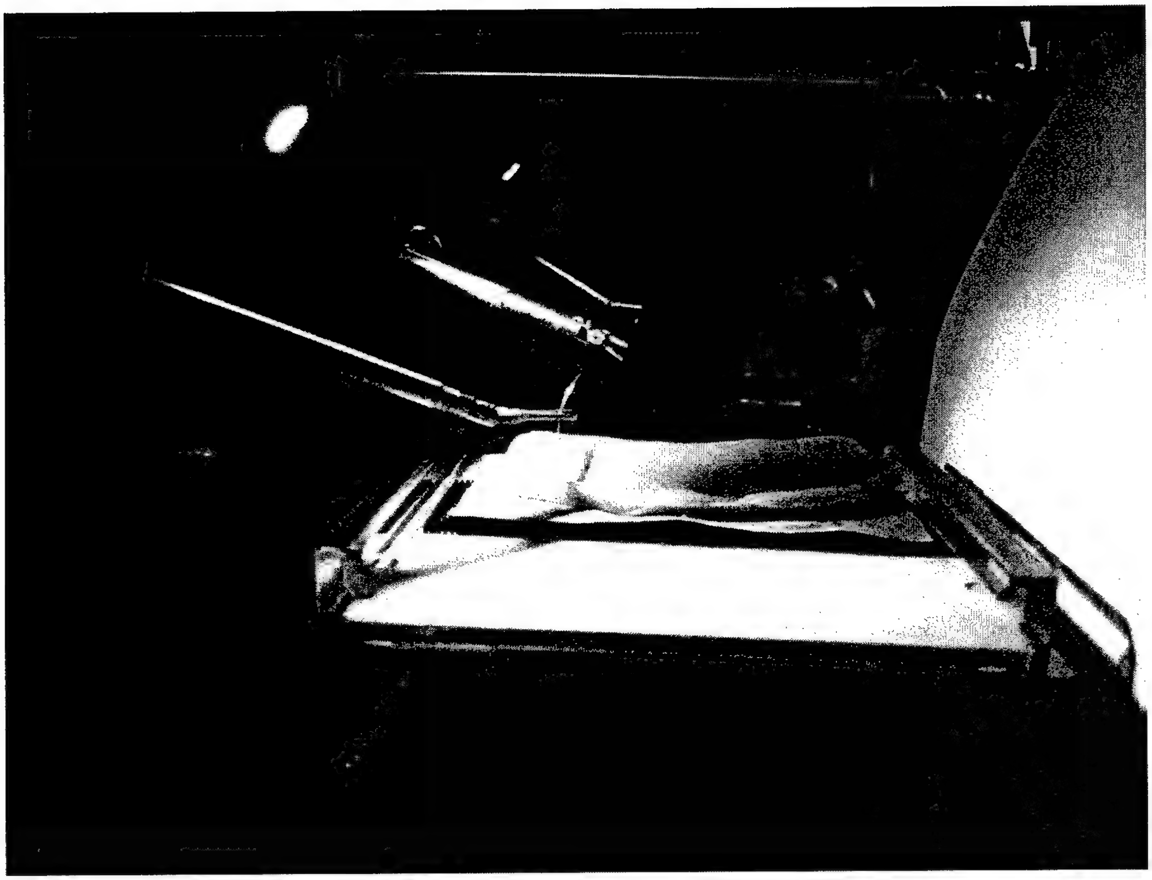

Figure 3. Placement of three running sutures into a Simulab silicone wound model.

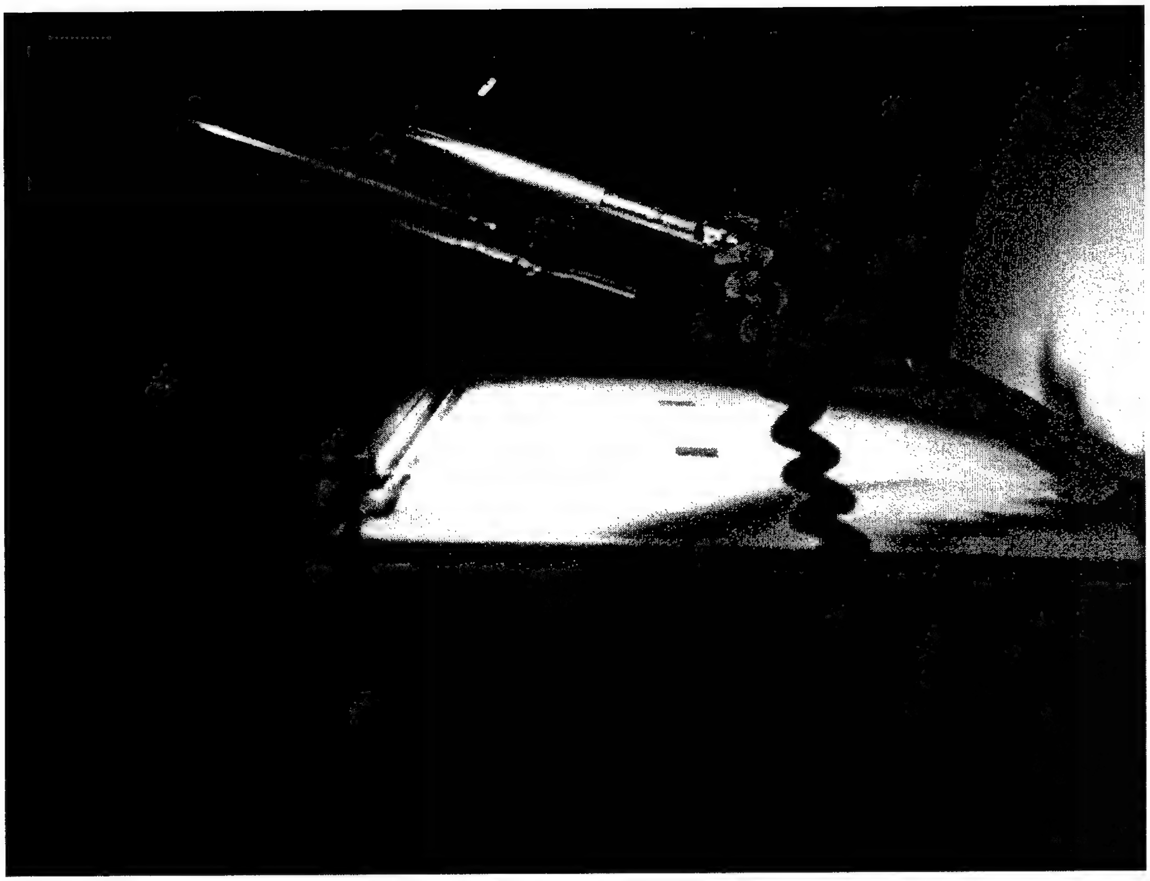

Figure 4. Running a 32-in ribbon from end-to-end using two needle holders.

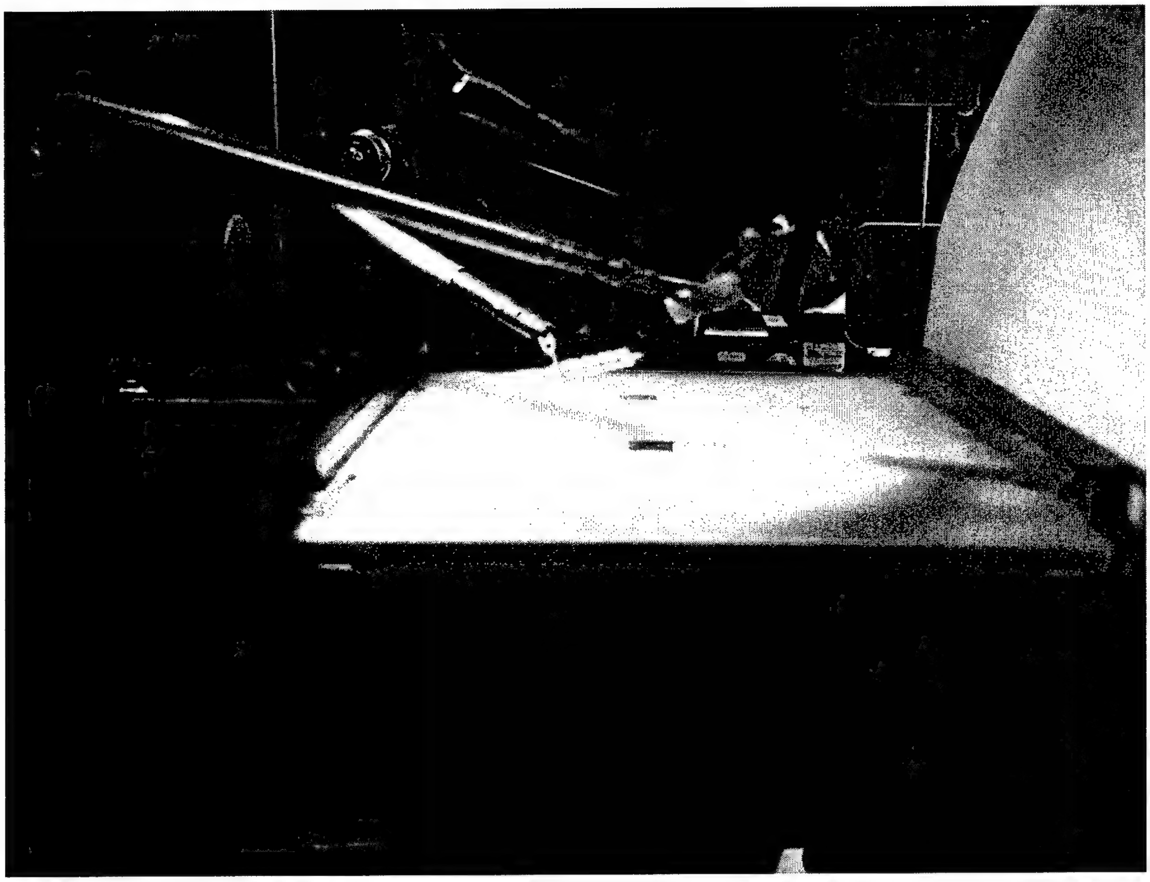

Figure 5. Preparing to pass a 1-in pipe cleaner through the lumen of a neoprene tube of ½-in length.

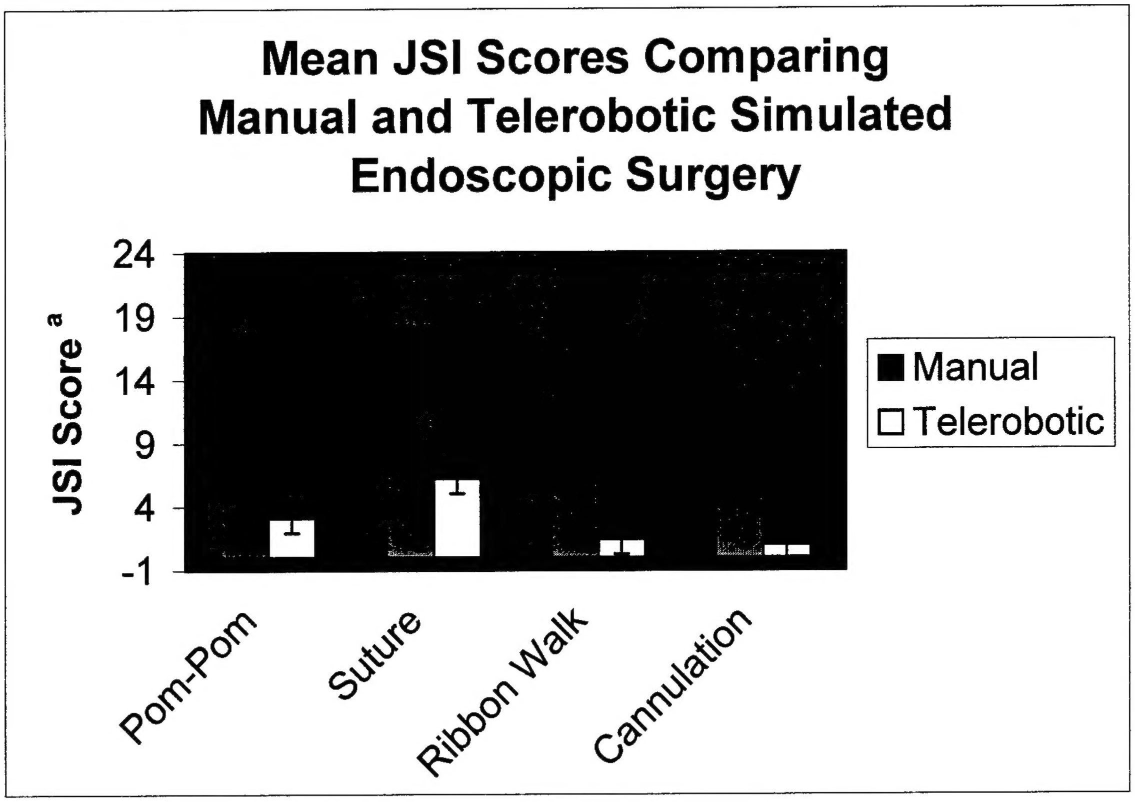

Figure 6.

[a] A higher JSI score is correlated with an increase mean incidence rate for upper extremity disorders.

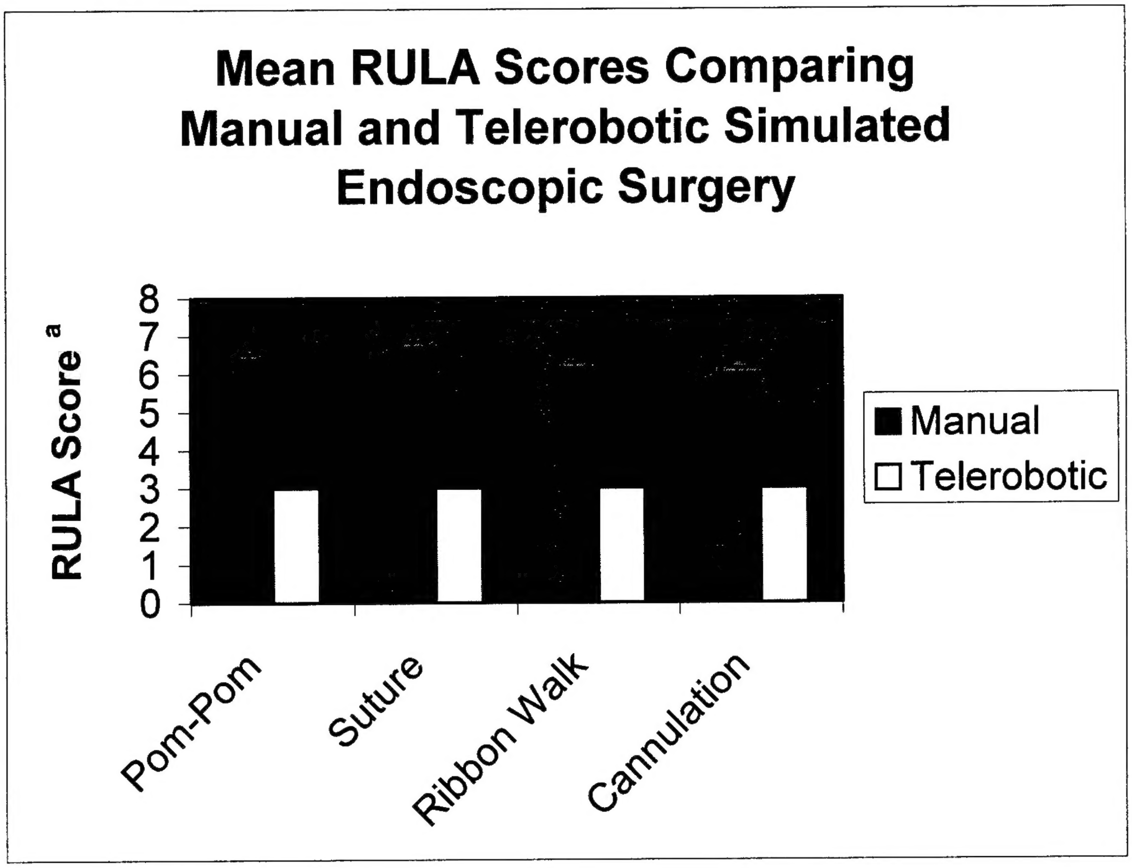

Figure 7.

[a] RULA scores range from 1 to 7. A score of 1 or 2 indicates a low probability of injury due to musculoskeletal loading. Higher scores estimate higher probability of injury.

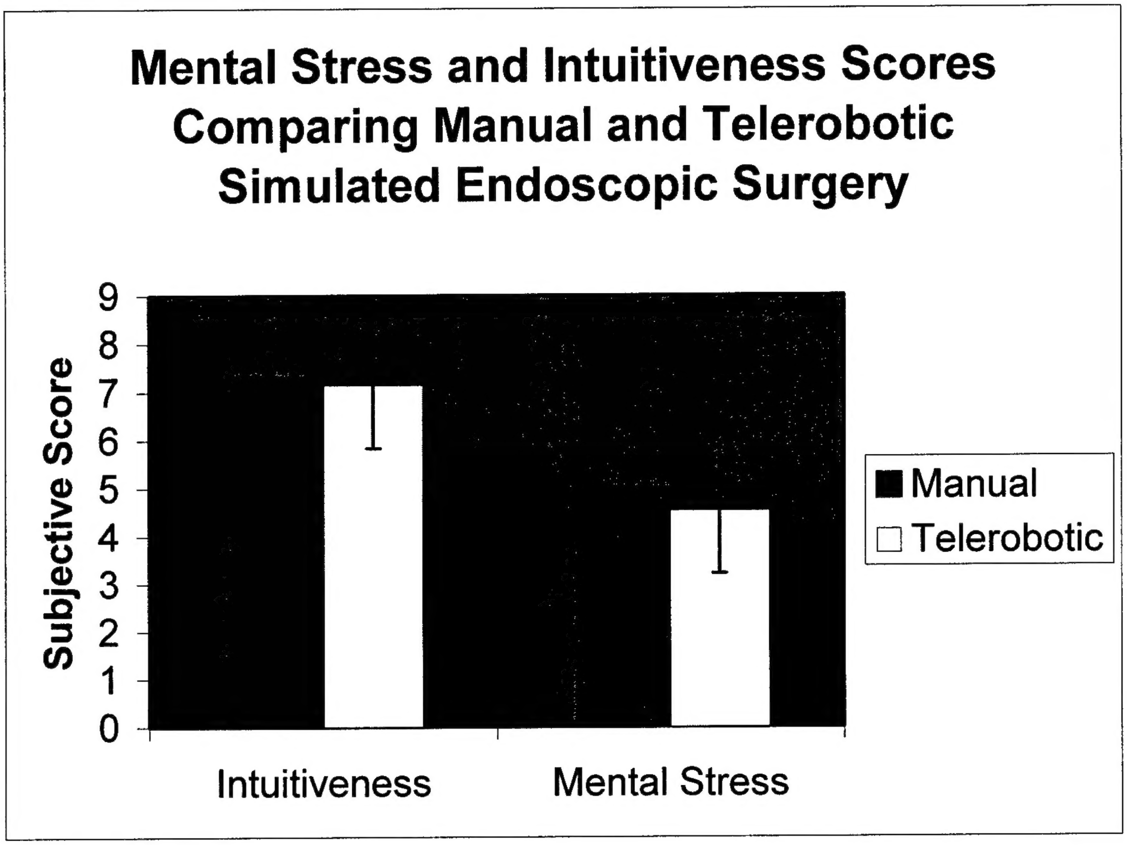
Mental Stress and Intuitiveness Scores
Comparing Manual and Telerobotic
Simulated Endoscopic Surgery
Subjective Score
9
8
7
6
5
4
3
2
1
0
Intuitiveness
Mental Stress
Manual
Telerobotic

Figure 8.

MEMORANDUM

Date: 12 Jan 04

From: Ernest Lee, Maj, MC, USAF
AFIT/Harvard

To: Kim Kubelick, LtCol, USAF, MSC, CHE

Subj: AFIT STUDENT REQUEST FOR CLEARANCE TO PUBLISH AND ORALLY PRESENT MANUSCRIPT

1. Respectfully request AFIT/PA clearance to publish required educational thesis (essentially ready for publication submission). Attached is a hard copy, CD backup, and AFIT/PA form.

2. Also request $100 AFIT student allowance for thesis.

E. C. Lee